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Shock Timing Techniques for Ignition Capsules on the NIF

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SHOCK TIMING TECHNIQUES FOR IGNITION CAPSULES ON THE NIF

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Abstract

Results from a series of shock trajectory measurements in planar liquid deuterium targets will set the pulse shape we use for ignition capsules at the National Ignition Facility. We discuss outstanding issues for this concept, in particular, ideas for certifying that the drive on a planar sample is the same as on a spherical capsule.

I. INTRODUCTION

We have described our plan for achieving proper ignition capsule shock timing during the ignition campaign at the National Ignition Facility (NIF) elsewhere [1]. We plan to use a VISAR [2] (velocity interferometry system for any reflector) to adjust the laser pulse shape (power as a function of time) until the first three shocks converge at a single radius and time. This experimental procedure greatly reduces our dependence on the accuracy of our drive and equation of state models: we do not need to know either drive temperatures or shock pressures very accurately in order to know that we have put the hydrogen fuel layer on a low adiabat.

The VISAR diagnostic measures the speed of the leading shock in cryogenic hydrogen, but that cannot be done inside an actual ignition capsule. In the ignition capsule, the spherical ablator pushes on the fuel, which is a layer of solid DT (deuterium-tritium). In the shock timing package that VISAR can monitor, a planar ablator pushes on a surrogate fuel layer of liquid DD (deuterium). We can use identical ablator material and thickness for the timing packages and capsule, but the hohlraum containing the timing package cannot be absolutely identical to the hohlraum containing the ignition capsule.

These differences give rise to two general categories of concerns: First, as we discuss in section II., the difference between spherical and planar drive, or between solid DT and liquid DD, might invalidate the pulse shape we derive by shooting the timing packages. Second, as we discuss in section III., the drive on the capsule might differ significantly from the drive on a timing package, even with the same laser pulse shape.

The brief response to the first concern is that we set the shock convergence depth in the liquid DD in order to compensate for the differences between the timing package and the capsule. We are still evaluating additional experiments that might address the second concern. However, we estimate that the drive difference between the shock timing package on the hohlraum wall and the capsule at the center of the hohlraum is in the range of two to three percent during the foot of the pulse. The capsule tolerates $\pm 12\%$ flux multipliers during the foot, which suggests the drive differences will not be large enough to require any corrections.

II. CONVERGENCE DEPTH SELECTION

The most important free parameter in the VISAR shock timing experiments is the depth in the liquid DD where the first three shocks converge. We select this depth on the basis of capsule and planar timing target models. The depth selection is supposed to compensate for any differences between planar and spherical geometry, or between liquid DD and solid DT layers.

Fig. 1 shows the capsule yield as a function of the selected convergence depth. To construct this curve, we ran a series of 1D simulations of the planar shock timing target, adjusting the x-ray drive pulse shape until the first three shocks converged at a given depth in the liquid DD; that

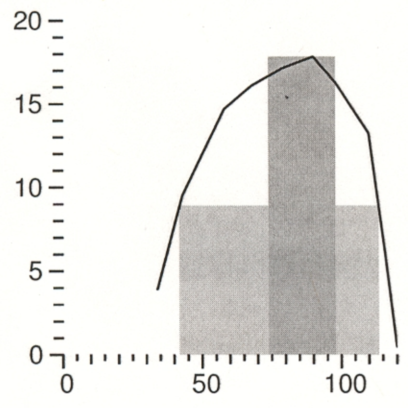

Figure 1: Capsule yield (MJ) as a function of shock convergence depth (μm). Note that the convergence depth is in the liquid DD layer of a planar shock timing target, while the yield is in an ignition capsule. Each point thus represents two different simulations, related by their identical x-ray drives. The shaded areas show the full width to half yield (light), and one third of that full width (dark).

depth is the abcissa in the plot. Next, we drove the ignition capsule with that pulse shape; the ordinate in the plot is the yield in that 1D capsule simulation. The shock timing procedure only determines the first 12 ns of the 17 ns drive pulse; we kept the final 5 ns of pulse shape fixed to generate this curve. (We doubt that a separate optimization of the rate of rise to the peak of the pulse for each point would significantly change the shape of this tuning curve.)

For this particular capsule, the x-ray drive which causes the first three shocks to converge 90 μm into the planar liquid DD layer gives the highest capsule yield. (This yield is very near the maximum this capsule can produce for any pulse shape with the same peak power and total energy.) The half yield points fall at convergence depths of 42 μm and 113 μm. However, these 1D yield calculations do not include all the other imperfections a real capsule must survive. Our experience is that when the effects of instabilities and asymmetry are included, a 1D yield curve becomes roughly a factor of three narrower. Hence, a more realistic estimate of the sensitivity of the capsule to convergence depth is that the capsule should function for pulse shapes corresponding to any convergence depth in the range 74 μm to 98 μm.

Of course, if the x-ray drive on the capsule were different than the x-ray drive on the timing package, or if our simulation codes did not properly account for the differences in the ablator curvature or in the liquid DD surrogate for solid DT, the pulse shape errors would not be restricted to shapes which produced shock convergence as in Fig. 1. The separate sensitivity to various pulse shape parameters is as follows: ± 0.60 ns to the launch time of the second shock, ± 0.36 ns to the launch time of the third shock, and $\pm 12\%$ flux multiplier during any one of the steps driving the first three shocks. Each of these ranges represents one third of the distance to the cliff in the 1D yield curve produced by varying that parameter alone.

III. DRIVE COMPARISONS

The easiest place to put the shock timing package is on the wall of the hohlraum. Our current plan is to make the shock timing hohlraums otherwise identical to the ignition hohlraums. Both are cryogenic, so similar gas fills should be possible, although it will be difficult to match the temperature and density gradients in the gas fills exactly. A few of the drive beams will need to be repointed in the shock timing hohlraums, in order to avoid hitting the timing package. We can arrange for the overall energy balance to be the same for the shock timing hohlraum as for the ignition hohlraum by adjusting the surface area of the shock timing package to match the capsule, and by adding some additional wall area (perhaps in the form of a baffle) to allow for the hole where we mount the timing package.

By matching the gross energetics of the hohlraums that drive the capsule and the shock timing packages, we believe we can produce very nearly the same x-ray drive at the surface of a shock timing package as at the surface of a capsule, when both hohlraums are irradiated with identical laser pulses. Simple viewfactor post-processing of detailed 2D hohlraum simulations indicates that the x-ray drive difference between the hohlraum wall, where the shock package sits, and the surface of the capsule is about 2% to 3% during the foot of the pulse. This is comparable to the drive variations from point to point on the surface of the capsule.

We could also repoint all of the beams slightly. We estimate that moving the outer cone 200 μm along the hohlraum wall changes the x-ray flux at the location of the shock timing package by about 1 % during the first part of the foot.

If the x-ray flux on the shock timing package is really within 2% of the flux on the capsule surface for the same laser pulse, then drive differences are not an issue. We are considering two types of experiments which might confirm that the drive on the capsule is what we expect. The first is to measure the ablator-fuel interface in the capsule using streaked radiography. The second is to mount the shock timing package in several alternate ways to check that we can model the drive variations.

III.A. Interface Trajectory Measurements

There is no way to directly observe the shocks in the fuel layer of an ignition capsule. However, we may be able to use a high resolution KB microscope to obtain a streaked radiograph of the fuel-ablator interface inside an ignition capsule. That interface trajectory might be a useful check that the pulse shape we set using the VISAR shock timing packages does, in fact, drive a capsule as we intended. We are still evaluating whether the information contained in the interface trajectory can play any role in setting the laser pulse shape. We know three very strong objections:

First, the side-on radiograph requires a backlighter. This diverts at least one quad, or 2 % of the total number of NIF beamlines, out of the hohlraum. (Even if the backlighter is placed inside the hohlraum, the beams that drive it would need much higher intensity than the drive beams during the foot of the ignition pulse.) There is enough energy to compensate for the missing quad(s) during the foot, but the point is, that is impossible to make the drive on the capsule during an interface trajectory measurement *identical* to the drive on the capsule during an ignition attempt. We are still left unable to *prove* at the 2 % level that we have measured the interface trajectory in an ignition capsule. We can already argue that the x-ray drive at the surface of a shock timing package matches the drive at the surface of an ignition capsule to within about 2 % in flux, on the same grounds that we could argue the drive during the interface trajectory measurement matched — namely, our confidence in our hohlraum modeling.

Second, we do not know what the interface trajectory is supposed to look like when the shocks are properly timed. Originally, we planned to measure the interface trajectory in the shock timing package simultaneously with the VISAR shock trajectory measurement. The timing package trajectory was to serve as a template for the correct capsule interface trajectory. However, the differences between the curved and flat ablator, and between the DT and DD payload, turn out to produce an interface trajectory difference that is much larger than what the capsule could tolerate. That is, a capsule which had the timing package trajectory would fail, as shown in Fig. 2.

Third, if we measure the interface trajectory and find it disagrees with our models, it provides us no information about the cause of the discrepancy. Would that mean the x-ray drive on the shock timing package is different than the drive on the (interface measurement) capsule? Or would it mean that our modeling of the expected capsule interface trajectory was wrong? We already account for the differences between ablator curvature and the DT–DD mass difference in our selection of the convergence depth in liquid DD. The shock timing package is designed to largely compensate for hydrodynamic modeling errors, so changing the model would change the predicted capsule interface trajectory by much more than it would change the shock convergence depth we select. So does an interface trajectory measurement allow us to make any laser pulse shape adjustments or not?

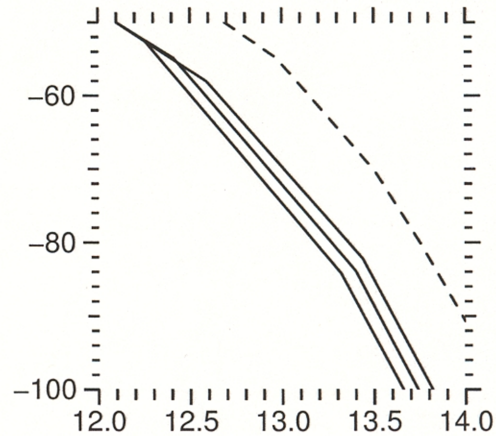

Figure 2: Three capsule interface trajectories during the period the second shock transits the fuel. The dashed line is the interface trajectory in the planar shock timing package driven by the same x-ray drive as the center capsule trajectory. The x-ray drive flux was multiplied by $\pm 12\%$ during the time between the launch of the second and third shocks, in the outer two capsule trajectories. These flux multipliers correspond to one third the distance to the 1D yield cliff, which represents our estimate of the maximum deviation of the drive this capsule can tolerate.

III.B. Alternate Package Placement

Instead of attempting to compare the unlike interface trajectories of shock timing packages and capsules, we could instead field identical shock timing packages in several alternative hohlraum environments. We could then certainly compare the x-ray drive for the different locations, in order to check our ability to model the small changes in drive from place to place inside a hohlraum. Fig. 3 sketches three different mounting schemes. The most interesting variants involve placing the shock timing package on a reentrant tube. We could place it quite near the location of the capsule surface in an ignition hohlraum. We can also directly test the effects of baffles or other minor adjustments for any of the mounting schemes. The VISAR will detect x-ray drive variations of order one percent, which is probably the most sensitive drive measurement we will have. Again, we know several objections to this plan:

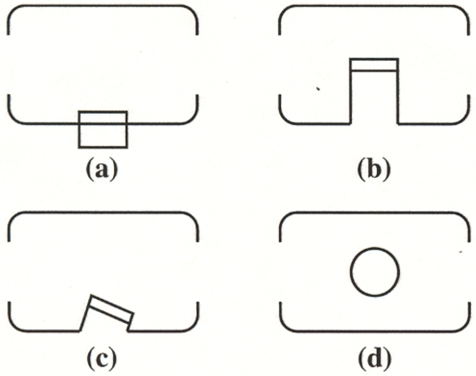

Figure 3: The baseline shock timing package mounting scheme is on the wall of the hohlraum (a). Alternatively, we could mount the shock timing package on reentrant tubes near the center of the hohlraum (b), or at some other angle (c). Which of these alternatives is the closest match to the drive at the surface of an ignition capsule (d)?

First, each mounting scheme is yet another hohlraum; all will produce drives that differ by a few percent. Measuring the differences between them is an interesting exercise, but it is unclear how to meaningfully extrapolate to the ignition hohlraum configuration we really care about.

Second, if the results of these tests disagree with our hohlraum modeling, it is unclear what action we should take. Although we will know the differences between the drive at the various locations we mounted the shock timing packages, we still will not know whether any of the locations matches the drive on an ignition capsule. Ultimately it will come down to a more or less subjective judgment of which alternative mounting scheme comes closest to matching the drive at the capsule surface. This does not differ in any obvious way from the situation in the absence of shock timing measurements in several alternative mounting geometries.

IV. CONCLUSION

We will use VISAR to set the foot of the laser pulse shape for ignition attempts at the NIF, by adjusting the timing of the first three shocks so they converge at a single point. We select the convergence depth to account for the hydrodynamic differences between the curved capsule ablator and solid DT fuel layer, and the flat shock timing package ablator and liquid DD surrogate fuel layer. We expect that the x-ray drive flux at the surface of the timing package will match the drive at the surface of the ignition capsule to within about 2%; the capsule tolerates flux multipliers of order $\pm 12\%$ during the foot.

We are considering two types of supplemental experiments as cross checks on this shock timing plan: First, we could measure the trajectory of the fuel–ablator interface in a capsule, and possibly also in the shock timing package. Second, we could mount the shock timing package in several alternative geometries. We do not yet know whether either or both of these supplemental measurements significantly increases our confidence that the foot of the laser pulse is correct. If the results of either did not match our models, it is unclear what, if any, action would be appropriate. For now, we regard these techniques as secondary experiments in the main shock timing plan.

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